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The Dark Matter, Gas and Galaxy Distributions in Abell 2218: A Weak Gravitational Lensing and X-ray Analysis

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ABSTRACT

We report on the detection of dark matter in the cluster Abell 2218 using the weak gravitational distortion of background galaxies. We find a highly significant, coherent detection of the distortion in the images of the background galaxies. We use HST images from the Medium Deep Survey to calibrate the suppression in the observed distortion due to atmospheric smearing. The inferred 2D mass distribution has a peak that is coincident with the optical and X-ray centroid. The qualitative distributions of the cluster light, the X-ray emission and the dark matter are similar and the projected total mass, gas, and light surface densities are consistent with a r^{-1} profile at distance of $r > 180''$ from the cluster cD galaxy. Using the weak lensing technique, we determine a lower bound for the total mass in A2218 of $(3.9 \pm 0.7) \times 10^{14} h^{-1} M_{\odot}$ within a fiducial aperture of radius $0.4 h^{-1} \text{Mpc}$. The associated cluster mass-to-light ratio is $(440 \pm 80) h M_{\odot}/L_{\odot B}$. The mass estimated by the weak lensing method is consistent with that inferred from the X-ray data under the assumption of hydrostatic equilibrium and we derive an upper bound for the gas-to-total mass ratio at $400 h^{-1} \text{kpc}$ of $M_{\text{gas}}/M_{\text{tot}} = (0.04 \pm 0.02) h^{-3/2}$.

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1. Introduction

One of the most compelling problems in astronomy today is understanding the distribution and nature of the ubiquitous dark matter, which dominates the dynamical evolution of much of the observable universe. Historically, much of the strongest evidence for dark matter comes from the virial analysis of clusters of galaxies. The high mass-to-light ratios ($M/L \sim 300 h$) thus obtained are supported by the observed high temperatures of the X-ray emitting gas and by the presence of giant arcs and arclets in the clusters. The nature and the extent of dark matter distribution in clusters, however, is not well understood. In the past, information regarding the dark matter distribution in clusters could only be extracted from dynamical studies of galaxies or from X-ray surface brightness data, under restrictive assumptions. For example, virial studies generally assume that galaxy orbits are isotropic and that the light traces the dark matter while analyzes of the X-ray data are based on the assumptions that the gas is in hydrostatic equilibrium within the cluster potential and is supported against collapse by thermal pressure. The results of these studies can be in considerable error if these assumptions are not valid. Gravitational lensing, on the other hand, is a well-understood physical process that directly probes the clusters' gravitational potential wells. Hence, studies of both the strong as well as the weak distortions in the images of faint, background galaxies induced by the clusters offer a unique opportunity to directly probe the cluster mass distributions in a model independent fashion, with the weak distortions being particularly suited for mapping the mass distribution out to large radii.

Mapping the dark matter distribution in clusters using the weak gravitational lensing effect is a subject of great modern interest and is rapidly becoming a mature subject. The procedure was pioneered by Tyson *et al.* (1990) and several groups have discussed techniques for acquiring and analyzing data (Bonnet & Mellier 1995; Kaiser, Squires & Broadhurst 1995; Fischer & Tyson 1995). The first fully developed algorithm for constructing cluster mass maps using the weak distortions was proposed by Kaiser & Squires (1993). This algorithm requires shear information extending out to infinity and applying it to data of finite spatial extent results in a mass map with a small but well understood bias at the edges of the data region. Minor modifications to the algorithm can correct for this bias and several modified techniques have been proposed (Kaiser & Squires 1995; Schneider & Seitz 1995; Seitz, C. & Schneider 1995; Seitz, S. & Schneider 1995). We emphasize that this affects only the 2-D reconstructions of the surface density. The aperture densitometry used here and in Fahlman *et al.* (1994) is entirely free of this bias.

The list of clusters analyzed using these algorithms is growing steadily and includes A1689 (Tyson *et al.* 1990; Tyson & Fischer 1995; Kaiser *et al.* 1995), Cl1409+52 (Tyson *et al.*

1990), MS1224+20 (Fahlman *et al.* 1994), Cl0024+17 (Bonnet *et al.* 1994; Mellier *et al.* 1994), Cl1455+22 and Cl0016+16 (Smail *et al.* 1994, 1995). A more complete list appears in the review by Fort & Mellier (1994). All of the methods, however, are limited in that the mass surface density can only be determined up to an additive constant. Broadhurst *et al.* (1994) have proposed a method for breaking this baseline degeneracy and the method was recently applied to A1689 (Kaiser, Broadhurst & Squires 1995).

In this paper, we present a study of A2218. A2218 has been studied extensively in several wavelengths. It is an optically compact (Butcher *et al.* 1983) Abell richness class 4 cluster (Abell *et al.* 1989) at redshift $z = 0.175$. It has a central velocity dispersion of 1370^{+160}_{-210} km/s (Le Borgne *et al.* 1992). A detailed photometric and spectroscopic study of the cluster center suggests that the cluster consists of two galaxy concentrations; the larger of the two centered about the sole cD galaxy in the cluster while the smaller concentration is located $67''$ to the southeast (Pello *et al.* 1988; Pello *et al.* 1992). Deep optical images of the cluster have revealed a wealth of arcs and arclets, with the arcs centered about both mass concentrations. The location and the morphology of the arcs suggest that the bulk of the cluster mass is associated with the galaxy concentration surrounding the cD galaxy. Kneib *et al.* (1995) have attempted to use the arcs to constrain the mass distribution within the central $\sim 130 h^{-1}\text{kpc}$.

A2218 also exhibits a strong Sunyaev-Zel'dovich effect (Birkinshaw *et al.* 1981; Birkinshaw & Gull 1984; Partridge *et al.* 1987; Klein *et al.* 1991, Jones *et al.* 1993; Birkinshaw & Hughes 1994) and has been well studied in the X-ray. It has an X-ray luminosity of 6.5×10^{44} erg/s in the 0.5-4.5 keV band (Perrenod & Henry 1981) and 1×10^{45} erg/sec in the 2–10 keV band (David *et al.* 1993). Its Einstein IPC image revealed a smooth circular profile (Boynton *et al.* 1982). The cluster has also been observed using both the ROSAT PSPC (Stewart *et al.* 1994) and HRI instruments. The peak of the X-ray surface brightness distribution is coincident with the location of the cD galaxy and the temperature of the X-ray emitting gas has been determined to lie in the range 6–8 keV (McHardy *et al.* 1990; Yamashita 1995).

In a recent study, Miralda-Escudé & Babul (1995) drew attention to an interesting puzzle concerning A2218: The mass in the central regions inferred from strong lensing distortions is greater than that determined using the X-ray observations by a factor of ~ 2 if the gas is assumed to be in thermal-pressure-supported hydrostatic equilibrium. This led them to speculate that perhaps the gas, at least in the central regions, may be partially supported against gravitational collapse by means other than thermal pressure (see also Loeb & Mao 1994). This mass discrepancy, if it extends out to larger radii, has important implications for quantities, such as the cluster gas fraction $M_{\text{gas}}/M_{\text{tot}}$, derived solely from X-ray data. Typically, the cluster gas fraction is estimated to be $M_{\text{gas}}/M_{\text{tot}} \sim 0.05h^{-3/2}$ (White & Fabian 1995; David, Jones & Forman 1995) a result that has been a source of much discussion (White 1992; Babul & Katz 1993; White *et al.* 1993). This value, however, may be an overestimate by as much as a factor of ~ 2 if the X-ray/lensing mass discrepancy discussed by Miralda-Escudé & Babul (1995) extends beyond the cluster core.

In this paper, we use the observed weak distortions in the images of faint background galaxies to determine the surface mass distribution associated with A2218 out to a distance of $\sim 600 \text{ h}^{-1}\text{kpc}$. We compare the distribution of total mass to that of the light and the gas (derived from ROSAT data). We also compare the lensing estimate of the total projected mass in the cluster with that determined using the X-ray data, and estimate the mass-to-light ratio for the cluster as well as the fraction of the total mass contributed by baryons. We compare the latter against constraints from nucleosynthesis.

2. Data Acquisition

A2218 was observed using the 3.6m Canada-France-Hawaii telescope on the nights of 1994 June 6-9. The detector used was the 2048 x 2048 Loral 3 CCD at prime focus with a pixel size of $0''.207$. Our observing strategy was to take relatively short (20 minute) exposures in each band and observe each field several times, with small random offsets.

Our I band observations of A2218 comprised of seven 20-minutes images centered on the cD galaxy — six of these were discarded due to bad seeing conditions — and two 20-minutes image of each field in a 2×2 overlapping grid about the cluster center. The two exposures of each field were offset by $\sim 10''$. The observations cover a $\simeq 145$ square arcminutes field, extending to a radius of $\simeq 6'.5$ ($\sim 750 \text{ h}^{-1}\text{kpc}$) from the cluster center. The seeing varied from FWHM= $1''.2$ during the first night to $0''.7$ during the second. We used only the best seeing data in our lensing analysis. We, therefore, have a total of 9×20 -minutes exposures on the cluster (one central field and 2×4 grid fields).

We also observed the cluster center in V, acquiring two 20-minutes exposures with seeing conditions of $1''.0$ FWHM. The V-band information, in conjunction with the I-band data, allowed us to identify the cluster galaxy sequence in the color-magnitude plane in order to facilitate an estimate of the light in the cluster. Also, the total integration of 40 minutes in the V-band was sufficient to yield an independent mass map out to a radius of $3'.5$ ($\sim 400 \text{ h}^{-1}\text{kpc}$) from the cluster center.

3. Data Analysis

The large number of exposures that we collected over the three nights of observing implies that in principle we ought to be able to construct a median sky flat. Unfortunately, all of the fields that we observed contain very luminous, extended galaxies. As well, several stars saturated and contaminated large portions of each exposure. The resulting median skyflat contains “shadows” of these objects. Attempts to mask the luminous galaxies and using only frames with large offsets did not result in any significant improvement. Consequently, we employed the median twilight flat. Dividing each image (after subtracting the bias) with the median twilight flat resulted in an

rms noise in the sky background on the individual images of 26.8 magnitudes per square arcsecond in I and 25.6 magnitudes per square arcsecond in V.

The data was calibrated against photometric standards in the globular clusters M92 and NGC 4147 (unpublished photometry from Davis 1990; see also Stetson and Harris 1988 and Odewahn *et al.* 1992) and Landolt (1992) standards in SA110. Color terms were found to be unnecessary in the transformation and the I and V zero points were determined with a formal error of less than 0.005 mag.

We identified objects on our images, and measured their position and size, using our standard procedure (Kaiser, Squires & Broadhurst 1995). Briefly, we smoothed each image with a family of Gaussian filters whose characteristic scales ranged from 0.5 to 100 pixels, varying in logarithmic steps of $d \ln(r) = 0.2$. The upper limit of the range for the filter scale was chosen so that the most luminous and extended galaxies would be comfortably contained within the filter. We tracked the peak trajectories (i.e. the peak significance as a function of smoothing radius) and assigned a radius to each object, r_g , corresponding to the radius of maximum significance (i.e. maximum signal-to-noise). For objects modeled as gaussian ellipsoids, this radius corresponds to the scale length.

For each object detected, we measured the shape, magnitude, and profile parameters. The magnitude of an object was estimated using an aperture of radius $3r_g$ (i.e. three times the radius of maximum significance). The weighted quadrupole moments, Q_{ij} , of the surface brightness distribution were determined using a bi-linear model for the local sky determined in a 16-32 pixel collar around each peak. The analysis employs a gaussian weighting function whose scale is matched to the object's radius of maximum significance. For gaussian objects, this choice is optimal.

The perturbation to the observed surface brightness due to a planar lens is $f'(\theta_i) = f(\theta_i - \phi_{,ij}\theta_j)$ where ϕ is the surface potential satisfying Poisson's equation $\nabla^2\phi = 2\Sigma/\Sigma_c = 2\kappa$, and $\phi_{,ij} \equiv \partial^2\phi/\partial x_i\partial x_j$. Here, $\Sigma_{crit}^{-1} = 4\pi G D_l \beta$ is the critical surface density, D_l is the angular diameter distance to the lens and $\beta = \max(0, \langle 1 - w_l/w_s \rangle)$. In an Einstein de-Sitter universe with $\Omega = 1$, the comoving distance w is defined as $w = 1 - 1/\sqrt{1+z}$. In the weak lensing limit, the effect of a planar lens can be represented as a perturbation to the intrinsic quadrupole moment of an object's surface light distribution.

We used the measured quadrupole moments to form a 2-component polarization

$$\epsilon_1 = \frac{Q_{11} - Q_{22}}{Q_{11} + Q_{22}} \quad \text{and} \quad \epsilon_2 = \frac{2Q_{12}}{Q_{11} + Q_{22}}. \quad (3-1)$$

Assuming that the $\phi_{,ij}$ terms are small and constant over the size of the galaxy image, we can relate the two polarization components (ϵ_1, ϵ_2) to the derivatives of the potential. For unit weighting and intrinsically circular objects, the polarization is related to the shear, γ , as $\epsilon_\alpha = 2\gamma_\alpha$ where $\gamma_1 = (\phi_{,11} - \phi_{,22})/2$ and $\gamma_2 = \phi_{,12}$.

For non-unit weighting (which is necessary to suppress divergent sky noise contributions), the first order shift in polarization induced by the shear is (Kaiser, Squires & Broadhurst 1995)

$$\delta\epsilon_\alpha = P_{\alpha\beta}^{shear} \gamma_\beta \quad (3-2)$$

where $P_{\alpha\beta}^{shear}$ defines the shear polarisability tensor. This tensor can be expressed as a combination of the angular moments of the surface brightness, the weight function and its derivatives. Consequently, it can be computed using quantities measured directly from each galaxy image. The details of the calculation are involved and are described in Kaiser, Squires & Broadhurst (1995). Here, we simply wish to highlight that the observed polarization is related to the shear (and hence the lens surface potential) in a simple linear manner.

Gravitational lensing is not the only process that can introduce perturbations in an image’s quadrupole moment. Various other effects, such as guiding errors, wind shake, etc., can cause similar distortions. Fortunately, these can be measured. In the absence of these non-gravitational effects, the images of the stars in the field would be circular. The smearing due to these effects introduces an anisotropy in their point spread function (psf). We model these non-gravitational distortions as a convolution of the actual light distribution of individual images with a small but highly anisotropic kernel $g(\vec{\theta})$. The calculation of the effect in the images is very similar to the above and the resulting shift in the polarization depends only on angular moments of $g(\vec{\theta})$. Specifically,

$$\delta\epsilon_\alpha = P_{\alpha\beta}^{smear} p_\beta \quad (3-3)$$

where $p_1 = q_{11} - q_{22}$ and $p_2 = 2q_{12}$ (Kaiser, Squires & Broadhurst 1995). To first order in p_α ,

$$q_{ij} = \int d^2\theta \theta_i \theta_j g(\vec{\theta}). \quad (3-4)$$

The smear polarisability tensor $P_{\alpha\beta}^{smear}$ again depends only the observed object surface brightness, the weight function and its derivatives.

The anisotropy in the psf (characterized by p_α) can be determined and corrected for as follows: We isolate the stars based on a size-magnitude cut and for each stellar image, we measure the polarization ϵ_α , which in effect is a measure of the perturbation since the actual images are expected to be circular. Since the smear polarisability tensor for intrinsically circular objects is diagonal and its elements can be determined from measured quantities, we can directly compute $p_\alpha = \epsilon_\alpha / P_{\alpha\alpha}^{smear}$ (no summation) as a function of position across the frame. Each object’s polarization is then corrected by $-P_{\alpha\beta}^{smear} p_\beta$, which restores the polarization to what would have been observed had the psf been perfectly isotropic.

4. Photometry

In Figure 1, we plot the half-light radius r_{hl} versus magnitude of all objects detected in the I-band data and in Figure 2, we do the same for the V-band data. The points enclosed within

the rectangles define the stellar loci. In constructing the catalogues, we masked the regions in the neighborhood of very bright stars as well as in the corners of the fields (these were affected by vignetting), and selected objects on each frame independently, requiring a significance of $\nu > 4\sigma$ over the local sky background. The significance threshold was determined after some experimentation with HST images. We found that this procedure, rather than a magnitude selection, was preferable as it resulted in a higher signal-to-noise when measuring the shear. We only retained objects that are detected on at least two of our nine exposures within a tolerance of 2 pixel positional coincidence. We used the same selection criteria to identify objects in our V-band data. In all, we detected 4444 objects in the I-band and 1355 in the V, corresponding to a surface density (of galaxies and stars) of $\bar{n}_I \simeq 30$ per square arcminute and $\bar{n}_V \simeq 28$ per square arcminute, respectively.

We used our catalogues to construct the I- and V-band number-magnitude counts. In Figures 3 and Figure 4, we compare these counts to the I-band counts of Lilly (1993) and I-, V-band counts of Woods *et al.* (1995). We computed the counts using all the objects (solid histogram) and after eliminating all objects that lie on the stellar locus in Figures 1 and 2 (dashed histogram). The counts are complete to $I \simeq 23$ and $V \simeq 24$. As the plots show, the counts in our frames are elevated with respect to the field counts, particularly at bright magnitudes. Removing the stars does not eliminate this discrepancy. The excess is mainly due to contamination by cluster galaxies, which we have not attempted to remove. The agreement with the field counts improves towards fainter magnitudes.

In Figure 5, we display the color-magnitude diagram for the central field. A red sequence of objects with a mean color of $V - I \simeq 1.6$ at the bright end is clearly distinguishable. We identified these objects as cluster galaxies. To extract this sample, we fitted a linear model to the color sequence and select objects with color within 0.2 magnitudes of the mean. In Figure 6, we plot the I-band number counts for the color selected sample of cluster galaxies. The sample contains 196 galaxies with $I < 20.25$. The number of objects per magnitude is roughly constant. Fitting the cluster luminosity function with a Schechter function $n(m) = A10^{-0.4m(\alpha+1)}$ yields $\alpha = -1$ for the faint end slope.

5. Light Distribution

We computed the galaxy surface number density distribution as well as the corresponding light distribution using all of the galaxies in the images. To reject obvious foreground galaxies, we

IvsR.ps

Fig. 1.— The half-light radius vs I magnitude for all objects in our field. We detect 4444 objects with significance $\nu > 4\sigma$ over the local sky background for a surface density of $\bar{n}_I \simeq 30$ per square arcminute. The rectangle delineates the stellar locus.

VvsR.ps

Fig. 2.— The half-light radius vs V magnitude for all objects in our field. We detect 1355 objects with significance $\nu > 4\sigma$ over the local sky background for a surface density of $\bar{n}_V \simeq 28$ per square arcminute. The rectangle delineates the stellar locus.

Icounts.ps

Fig. 3.— The counts per square degree per magnitude from the I-band data. The solid histogram is using all objects; the dashed histogram comes from removing bright stars ($I < 21.5$). The solid line is a fit to the Woods *et al.* (1995) counts. At the brighter magnitudes, we see an excess in the counts due to the cluster galaxies. At $I \simeq 22$ the counts agree reasonably well with the field counts. The sample is complete to $I \simeq 23$.

Vcounts.ps

Fig. 4.— The counts per square degree per magnitude from the V-band data. The solid histogram is using all objects; the dashed histogram comes from removing bright stars ($V < 22.5$). The solid line is a fit to the Woods *et al.* (1995) field counts.

ColourvsI.ps

Fig. 5.— The V-I color vs I for the center field.

ClusterCountsI.ps

Fig. 6.— The counts per square degree per I magnitude for objects with $I < 20.25$ and color ± 0.2 from a linear fit to the color sequence. The dashed line shows the Woods *et al.* (1995) field counts.

applied a very conservative mask. We removed the bright spiral galaxy to the northeast of the cD galaxy but allowed its companion to remain. The giant elliptical to the east is very likely to be a foreground object as well. We allowed it to remain in the calculation of the light distribution however, as there is a significant overdensity of galaxies in its vicinity suggesting that there is perhaps a group or small cluster associated with the galaxy.

We display the light and galaxy surface number density as contour plots superposed on the optical image of the cluster in Figures 7 and 8, respectively. The contours have been smoothed with a Gaussian smoothing scale of $0''.67$ and are broadly similar. The peak of the light map (Figure 8) is centered on the primary galaxy clump (the one containing the cD galaxy) in the cluster and the surface brightness drops off smoothly towards the cluster periphery. In the central region, the contours are elliptical, with the major axis aligned with the primary and secondary galaxy concentrations as well as the chain of bright galaxies stretching away from the cD galaxy in the northwest direction. At distances greater than $\sim 2'$ from the cD galaxy, the contours show a weak extension towards a giant elliptical galaxy to the east of the cD galaxy. The surface number density plot (Figure 7), has a very similar morphology. The peak and orientation of ellipticity matches that of the light map. The extension to the east is more evident and extends beyond the giant elliptical galaxy. In addition, there are extensions roughly to the north, south, and west/northwest. Employing the color selected bright galaxy sample in place of the entire galaxy sample yields a very similar galaxy number density and light distribution. The peak and central ellipticity match that of the entire galaxy population in the images. There is some weak evidence of the extension towards the east, but it is not well resolved in the color selected sample.

While qualitative descriptions of the light and galaxy distributions are useful, to understand the nature of the distributions and to make comparisons with the distributions of gas and total mass in the cluster, we need to be more quantitative. The usual approach is to compute the mass-to-light ratio as a function of radius. In principle, we can use the excess in the number of galaxies over the field counts to estimate the number of galaxies in the cluster and hence, estimate the cluster light; however, we prefer a more simple approach. We make two measurements, which place upper and lower bounds on the cluster light.

To determine the upper bound, we estimate the light contributed from *all* galaxies in our observations. This sample will certainly contain many field galaxies and hence yields an overestimate of the light contributed by the cluster galaxies. We work directly with the co-added V image and compute a cumulative, circularly averaged, radial light profile centered on the cD galaxy. We select all objects that were detected on both of the V-band images and identify as

numberonimage.ps

Fig. 7.— The smoothed surface number density of galaxies (contours) placed on the optical I-band image of the cluster center. The contours have been smoothed with a gaussian of scale length $0''.67$. North is to the right; East is up.

galaxies all objects having half-light radius greater than 1.2 times the mean stellar half-light radius. We mask all the galaxies on the image and determine a light profile of the resulting image. The light profile of the galaxies is then determined by subtracting the profile of the masked image from that of the unmasked image.

To establish the lower bound, we do a similar analysis using only our bright color selected galaxy sample. At the bright end, we do not expect much contamination from the field galaxies; most galaxies ought to be cluster members. The color selected sample, however, excludes all faint ($I > 20.25$) cluster galaxies as well as bright cluster galaxies that lie outside the color sequence. Hence, the resulting cumulative light profile corresponds to a lower bound on the total cluster light.

The two cumulative light profiles described above are shown in Figure 9. The solid line corresponds to the light profile computed using all the galaxies and the short-dashed line corresponds to that computed using only the bright, red cluster galaxies. At a fiducial radius of $3'.5$ ($\sim 400 h^{-1}\text{kpc}$), the total apparent magnitude is $V = 13.68$ while that computed using only the red galaxies is $V = 13.96$. These two estimates place an upper and lower bound on the cumulative magnitude at this radius. We determine also the cumulative V-band profile using all galaxies in the more spatially extended I-band images, converting from I to V by applying a color transformation of $V - I = 1.6$, which matches the bright end of the color sequence. In the region where the two profiles overlap, the latter profile (the long-dashed line in Figure 9) agrees very well with that computed directly using the V-band data.

It is customary to quote the luminosity (or the luminosity profile) in the B-band. We estimate the B-band luminosity for A2218 using our apparent V-magnitudes as

$$L_B = 10^{0.4(M_{B\odot} - V - (B - V) + DM + K)} L_\odot \quad (5-1)$$

where $M_{B\odot} = 5.48$ is the total solar B magnitude. We apply a K-correction of $K = 0.3$ and a color transformation of $B - V = 0.93$, as suggested by the data in Coleman, Wu and Weedman (1980). Since A2218 is at redshift $z = 0.175$, its distance modulus is $DM = 38.69$ (for $\Omega = 1$ and $h = 1$).

The cumulative B-band luminosity, as a function of radius, is plotted in Figure 10. Within the central $\sim 100''$, the profile agrees reasonably well with that of Kneib *et al.* (1995). At larger radii, the cumulative light in the cluster increases linearly with r , suggesting that the optical surface brightness varies with radius as $1/r$. At a fiducial radius of $3'.5$ ($\sim 400 h^{-1}\text{kpc}$), the estimated B-band luminosity of the cluster is in the range $6.8\text{--}8.8 \times 10^{11} h^{-2} L_\odot$.

lightcontour.ps

Fig. 8.— The smoothed light from all the galaxies (contour) superimposed on the optical image of the cluster field. The light contours have been smoothed with a gaussian of scale length $0'.67$. North is to the right; East is up.

6. Lensing Analysis

As discussed in §3, we used the stellar psf to determine and correct for the distortions introduced by non-gravitational influences in the images of all objects on a given frame (see equations 3-3 and 3-4). We found that the spatial variations in the psf, over a given image frame, is well modeled by a second-order polynomial. The constant term in the polynomial is benign for our lensing analysis – a uniform shear does not affect our reconstructions of the surface mass density. However, the gradient and the higher order terms are important and contaminations affecting these quantities are more worrisome. In the uncorrected images, we found a gradient in the stellar psf that corresponded to a shift in polarization of 4% across each frame. In the cluster outskirts, this is approximately equal to the signal we are trying to measure, and so it clearly must be removed. In addition, we also found that the distortions in the stellar psf, particularly the values of the second-order terms in that expansion, varied from frame to frame. This not too surprising and is likely due to the unintended rotation of the bonette between exposures. These second order terms, however, introduce only a small correction and their inclusion in the analysis resulted in only a very slight improvement over the gradient model, as measured by the change in the residual chi-square value.

We show the psf for one of our frames in Figure 11. The raw frame (left panel) has a mean $\epsilon_1 = -0.07$. The right panel shows the polarization after the correction is applied. In this case, we are left with a residual mean polarization of 0.0008. In all of our corrected frames, the residual polarization is ≤ 0.005 .

As discussed previously, we identified as galaxy candidates those objects, on each corrected frame, that appear on at least two frames and have a half-light radius at least 1.2 times larger than the stellar psf ($r_{hl} > 0''.26$). We then designated those galaxies with magnitudes $I > 21$ as background objects. This yielded a catalogue containing 2370 background galaxies over an area of 145 square arcminutes around the cluster center. We converted the individual polarization estimates to shear measurements according to equation 3-2.

Next, we calibrated the effect of atmospheric seeing, which tends to diminish the shear. We used the Medium Deep Survey (MDS) data from the Hubble Space telescope to accomplish this. The raw HST images have roughly twice the resolution of our CFHT data and are unaffected by the atmosphere. The combination of the two data sets allowed us to quantify the damping of the shear due to atmospheric smearing. Using the WFPC2 fields, we constructed a mosaic that

cumM.ps

Fig. 9.— The cumulative V magnitude as a function of radius from the cD galaxy. The solid line comes from the V-image; the short-dashed line is the red cluster galaxy contribution to the light. The long dashed line is the calculation done on the I-band image with a transformation to V being done with a constant color shift of $V - I = 1.6$.

is twice the size of our survey field and applied a constant shear of amplitude $\gamma = 0.15$. The latter simulates well the effect of lensing on the galaxy population by a low redshift cluster. We then rebinned the pixel size to match the resolution of our CFHT data, and applied a gaussian smoothing to simulate the observed seeing conditions. Strictly, this should slightly underestimate the dilution of the measured shear due to seeing as the observed psf has a small extended wing compared with a gaussian. However since we compute centrally weighted quadrupole moments, the slight extension of the psf contributes a minimal amount and the results presented here do not change if we use the shape of the psf measured from our data. Finally, we added sky noise comparable to that in our observations. The resulting image was processed in exactly the same manner as the real data. Since we are using real galaxy images as input and are simulating, as nearly as possible, the observing conditions we had for our program, we are able to empirically calibrate the loss in the shear signal. In this fashion, we also do not need to model the intrinsic distributions of galaxy sizes, magnitudes and ellipticities.

Subjecting the simulated CFHT images to the same significance, size and magnitude cuts as the data, we found that for the I-band data we were able to recover $(50 \pm 7)\%$ of the input signal, with the dispersion being estimated from the scatter over several simulations. All of our shear estimates are boosted by this factor. In Figure 12, we display the mean shear calculated on a 16×16 grid placed on the I-band image of the field about A2218. The grid calculation ensures that all points are strictly independent. The visual pattern is suggestive and the tangential alignment around the cD galaxy is evident.

In the upper panel of Figure 13, we plot the mean radial tangential shear profile, using the cD galaxy as the center. The upper dashed line shows the prediction for a singular isothermal sphere with the observed velocity dispersion of 1370 km/s (Le Borgne *et al.* 1992), while the lower line corresponds to $\sigma = 1000$ km/s. In the lower panel, we display the statistic (Kaiser *et al.* 1995)

$$\begin{aligned} \zeta(\theta_1, \theta_2) &= 2(1 - \theta_1^2/\theta_2^2)^{-1} \int_{\theta_1}^{\theta_2} d\ln(\theta) \langle \gamma_t \rangle \\ &= \bar{\kappa}(\theta_1) - \bar{\kappa}(\theta_1 < \theta < \theta_2) \end{aligned} \quad (6-1)$$

$$(6-2)$$

which measures the mean surface density interior to θ_1 relative to the mean in an annulus $\theta_1 < \theta < \theta_2$. The dashed lines show the predictions for the two isothermal sphere models assuming that the cluster extends into the control annulus.

We repeated this analysis for our V-band data and display the corresponding radially averaged tangential shear profile and the ζ statistic in Figure 14. The similarity between the V- and I-band

cumL.ps

Fig. 10.— The cumulative luminosity as a function of radius from the cD galaxy. The lines are as described on Figure 9.

results is reassuring; the fact that the measured shear estimates are reproducible in different wavelengths implies that we are not introducing some wavelength-dependent bias in our analysis.

The plots in Figures 13 and 14 show that for $r > 180''$ ($r > 340 \text{ h}^{-1}\text{kpc}$), the measured tangential shear is consistent with that expected from a singular isothermal mass distribution with the observed velocity dispersion ($\sigma = 1370 \text{ km/s}$). Interior to this, the measured shear more closely corresponds to that expected from a $\sigma = 1000 \text{ km/s}$ isothermal mass distribution. One can interpret this trend as implying that the velocity dispersion characterizing the mass distribution in the cluster is $\sigma \sim 1000 \text{ km/s}$ out to a radius of $r = 100''$ ($r = 190 \text{ h}^{-1}\text{kpc}$) from the cD galaxy and then, smoothly increases to $\sigma \sim 1370 \text{ km/s}$ at larger radii. Alternatively, the cluster velocity dispersion may very well be constant throughout the cluster but the observed value of shear in the central region is suppressed because the sample of galaxies used to compute the shear is strongly contaminated with cluster galaxies. Certainly, we can get an indication that shear suppression due to cluster contamination is indeed happening by focusing only on those galaxies with colors redder than the main cluster sequence. By and large, these galaxies will be background objects. The resulting mean tangential shear at small radii is greater than that determined using all galaxies. Unfortunately, the number of red background galaxies is small and hence, we are unable to offer anything more definitive. In any case, our conversion of the measured quadrupole moments of the galaxy image into shear is based on the assumption that the derivatives $\phi_{,ij}$ of the surface potential are small. This assumption certainly breaks down in the central regions of the cluster.

At large radii, the cluster contamination is not an important consideration. Each of the points in Figure 13 with $r > 180''$ corresponds to an average over ≥ 300 galaxies. Furthermore, the measured shear is small (of the order of 10%) and hence, we are confident about the results yielded by our analysis.

Turning back to the actual distribution (as opposed to the radial profile) of shear across cluster, we used the maximum probability extension of the original inversion algorithm (Kaiser & Squires 1993; Kaiser & Squires 1995) to construct a map of the dimensionless surface (total) mass density, κ . This modified algorithm takes into account the finite nature of the data and yields an unbiased estimator of the surface mass density with very low noise properties. In Figure 15, we superpose the contour map of the reconstructed κ on the optical image of the cluster. The contour maps has been smoothed with a gaussian of scale length $0'.67$. The location of the dominant peak of coincides with the position of the cluster cD galaxy with a secondary peak approximately $3'$

stellarpsfcorr.ps

Fig. 11.— The point spread function for one of the I-band images. The left panel shows the major axis of objects identified as stars in the field. The right panel shows the major axis of the stars after the correction has been applied. We use a frame dependent, second order model for the psf. Here the raw frame had a net $\epsilon_1 = -0.07$, while after the correction is applied the residual $\epsilon_1 = 0.0008$. The residual polarization was $< 0.5\%$ for all of our corrected frames.

away towards the east. There is, however, no resolved peak associated with the secondary galaxy concentration although the isodensity contours in the vicinity of the cD galaxy are elongated towards the secondary concentration. Away from the cD, the isodensity contours show extensions towards the north, west, east and south-by-southeast, with the eastern extension forming a bridge between the two peaks.

In order to convert κ , the dimensionless surface density, into a physical quantity, we need to determine the critical surface density $\Sigma_{crit} = (4\pi G D_l \beta)^{-1}$. For low-redshift clusters, the value of Σ_{crit} is only weakly dependent on the background galaxy redshift distribution (Kaiser, Squires, & Broadhurst 1995). We adopted a value of $\beta = 0.6$ as suggested by an extrapolation of the observed redshift distribution (Lilly 1993, 1995; Tresse *et al.* 1993) to fainter magnitudes and hence, $\Sigma_{crit} = (7.0 \pm 0.7) \times 10^{15} \text{ h M}_\odot/\text{Mpc}^2$, where we assumed a 10% uncertainty in β . We note that the value of β is not very sensitive to the model used to estimate the redshift distribution; for example, the model for the faint galaxies of Gronwall & Koo (1994) yields $\beta = 0.59$.

In Figure 16, we plot the 2D mass profile of the cluster. The solid line is the mass profile of a singular isothermal model with a velocity dispersion of 1370 km/s and whose mass profile extends into the control annulus. We also plot the projected mass at $r = 21''$ ($40 \text{ h}^{-1}\text{kpc}$), the presumed critical radius determined from one of the giant arcs with redshift $z = 0.7$ (see Miralda-Escudé & Babul 1995), as well as the projected mass at $r = 68''$ ($130 \text{ h}^{-1}\text{kpc}$) implied by the mass model proposed by Kneib *et al.* (1995) in order to account for the positions and the morphologies of the giant arcs. The mass estimate of Kneib *et al.* (1995) is in reasonable agreement with the $\sigma = 1370 \text{ km/s}$ isothermal prediction at a radius of $\simeq 1'$ — their mass estimate actually corresponds to a singular isothermal with a velocity dispersion of $\sigma = 1200 \text{ km/s}$ — but is higher than the weak lensing result. This is not surprising since the the weak lensing mass estimates at small radii are expected to underestimate the true mass, as we have already discussed. At radii where we have confidence in the weak lensing results ($r > 180''$), the projected mass profile is consistent with that of the $\sigma = 1370 \text{ km/s}$ isothermal model (i.e. $\Sigma_{tot} \sim 1/r$) although there is a slight indication that the mass profile might be slightly steeper.

7. X-ray Analysis

Abell 2218 was observed by ROSAT both with the PSPC (position sensitive proportional counter) on 1991 May 25-26 for 44530 seconds and with the HRI (high resolution imager) on 1994 January 5-7 and 1994 June 17-19 for a total 35809 seconds. The X-ray emission originates from

etonlight.ps

Fig. 12.— The mean shear calculated on a 16×16 grid placed on the I-band image of the field. The length of the vector is proportional to the shear with the longest line being equivalent to a shear of 65%.

etprofI.ps

Fig. 13.— The radially averaged tangential shear from the I-band data. The dashed line are predictions of the isothermal sphere model with $\sigma = 1000, 1370$ km/s respectively. The bottom panel shows the statistic which measures the mean κ interior to θ , relative to the mean κ in the annulus $\theta < \theta' < 373''$. The error bars are estimated from the orthogonal shear component - this will overestimate the error if the shear pattern is non-circular.

etprofV.ps

Fig. 14.— The radially averaged tangential shear from the V-band data. The solid lines are the isothermal sphere models with $\sigma = 1000, 1370$ km/s. The errors are calculated from the second moment of the orthogonal shear component.

massonI.ps

Fig. 15.— The reconstructed surface density using the maximum probability extension to the original Kaiser-Squires algorithm. The contours have been smoothed with a gaussian with scale length $0'.67$.

MassVsR.ps

Fig. 16.— The 2D mass profile of the cluster. The points with errors are the estimates from the weak lensing with the uncertainties calculated from adding the errors in κ and Σ_{crit} in quadrature. The mass calculation uses the surface density interior to a radius relative to that in the control region extending to $\theta = 370''$. The solid and dashed lines are isothermal sphere predictions for $\sigma = 1370, 1000$ km/s respectively, assuming the cluster extends into the control annulus. The **X** represents the mass estimated by Kneib *et al.* 1995 by modeling the giant arcs. The triangle is the mass measured by Miralda-Escudé & Babul (1995) at the critical radius from the cD galaxy.

the hot intracluster medium (ICM) contained within the gravitational potential of the cluster. A contour plot of the HRI X-ray surface brightness, superposed on the optical image of the cluster, is presented in Figure 17. The X-ray map has been smoothed with a gaussian filter of scale 0'23. The X-ray contours are elliptical and the position angle of the major axis varies with distance from the central peak. This peak is coincident with the cD galaxy and there is no evidence of enhanced emission (a secondary peak) associated with the second of the two galaxy concentrations (see also Kneib *et al.* 1995) although at distances of 1'5 to 2' from the central peak, the X-ray contours show extensions in the southeast (encompassing the secondary mass concentration), north and west/west-by-northwest directions.

The radial profile of the observed X-ray surface brightness of A2218 (see Figure 2 of Miralda-Escudé & Babul 1995) can be well fit by a function of the form

$$S(r) = S_0 \left[1 + \frac{r^2}{r_c^2} \right]^{-3\beta+1/2} \quad (7-1)$$

where S_0 is the central surface brightness and r_c is the core radius (eg. Fabricant & Gorenstein 1983). To minimize contamination by the background, we only used the PSPC data in the 0.5 to 2 keV band and fitted the radial profiles for each of the four quadrants separately. The resulting values of r_c and β are presented in Table 1. To account for the possible smoothing of the X-ray data by the point spread function of the detector, we applied Lucy's deconvolution algorithm (Lucy 1974) to the image and performed fits to the resulting surface brightness profiles. The difference between values of β and r_c for the original and the deconvolved images is insignificant. As the dispersion in r_c is small, the fits show that X-ray surface brightness can be reasonably approximated as being circularly symmetric, with errors due to deviations from circular symmetry being relatively small.

The above expression for the X-ray surface brightness profile can be readily inverted to yield the gas density profile

$$\rho(r) = \rho_0 \left[1 + \frac{r^2}{r_c^2} \right]^{-3\beta/2}. \quad (7-2)$$

The central density ρ_0 is proportional to the central electron density n_{e0} , which is given by

$$n_{e0} = \frac{1.2 S_0 (1+z)^4}{4\pi\Lambda r_c} \frac{\Gamma(3\beta)}{\Gamma(1/2)\Gamma(3\beta-1/2)} \quad (7-3)$$

where S_0 is expressed in terms of arcmin^{-2} , and Λ is the emissivity of the gas in the observed energy band. Formally, the above inversion assumes that the gas is isothermal and spherically

xrayonimage.ps

Fig. 17.— The HRI X-ray surface brightness profile placed on the optical image of the cluster. The contours have been smoothed with a gaussian with scale length 0'23. North is to the right; East is up.

distributed. However, for gas at temperatures of 2–15 keV, the photon count rate in the 0.5 to 2 keV PSPC energy band is relatively insensitive to temperature variations; for example, the values of n_{e0} computed assuming a gas temperature of $T = 3$ keV and $T = 8$ keV differ only by 5 to 10%. The values of n_{e0} associated with the fits to the X-ray surface brightness profiles in each of the four quadrants are given in Table 1. At large radii, the gas surface density falls off as $\sim 1/r$ and since the X-ray surface brightness profile extends out to a projected distance of at least $\sim 9'$ ($\sim 1 \text{ h}^{-1}\text{Mpc}$), so must the gas distribution.

Integrating the radial gas density distribution yields the total gas mass profile for the cluster. In Figure 18, we show the projected (2D) gas mass profile. The error bars reflect the uncertainties in the values of parameters (β , r_c) characterizing the surface brightness profile as well as in the value of the gas temperature at each radius. At the fiducial radius of 3.5 ($\sim 400 \text{ h}^{-1}\text{kpc}$), the projected gas mass is $(1.65 \pm 0.5) \times 10^{13} \text{ h}^{-5/2} M_\odot$. Unlike the weak lensing mass estimate, the gas mass corresponds to the *actual* projected mass within a specified radius.

Under the assumption that the intracluster gas is in thermal-pressure-supported hydrostatic equilibrium in the cluster potential, the X-ray data can also be used to estimate the total gravitational mass of the cluster:

$$M(< r) = -\frac{kT(r)r}{G\mu m_p} \left[\frac{d \ln \rho_g}{d \ln r} + \frac{d \ln T}{d \ln r} \right]. \quad (7-4)$$

This calculation, however, requires the knowledge of the temperature distribution in the cluster. The first ASCA observations give a temperature of $T=8$ keV (Yamashita 1995) while GINGA observations yield an overall flux-weighted ICM temperature of $6.7^{+0.5}_{-0.4}$ keV (McHardy *et al.* 1990). A spectral analysis of the ROSAT/PSPC data, on the other hand, yields temperatures in the range of 3 to 5 keV. In this analysis, we simultaneously fitted the temperature, the hydrogen column density and the metallicity in different annuli. The temperature determinations for the different radial bins agree within the error bars and are always lower than the GINGA or the ASCA determinations.

The discrepancy between our ROSAT-based determination of the gas temperature in A2218 and the temperature measurements from ASCA or GINGA may simply reflect the fact that the analysis of the ROSAT data does not provide as accurate results as the other two satellites in cases where the peak of the ICM energy spectrum lies beyond the energy range of the PSPC. Alternatively, the discrepancy in the temperature determinations may indicate the presence of gas components with different temperatures, with the PSPC data being dominated by emission from the colder components while the ASCA and the GINGA data is dominated by the high temperature component. Indeed, a new analysis of the ASCA data suggests that the gas temperature declines away from the cluster centre (Mushotsky 1995). We did attempt a two temperature fit to the X-ray spectra but did not find any improvement.

As noted above, our spectral analysis also yields a measure of the hydrogen column density and metallicity. We find a hydrogen column density in the range $1\text{--}3 \times 10^{20} \text{ cm}^{-2}$ and a metallicity of

$0.2^{+0.2}_{-0.2} Z_{\odot}$. The metallicity agrees very well with the GINGA and the ASCA results of $0.2^{+0.2}_{-0.2} Z_{\odot}$ (McHardy *et al.* 1990) and $0.18 Z_{\odot}$ (Yamashita 1995), respectively.

It should be noted that the results of the spectral analysis depend weakly on the adopted value for the background. In our analysis, we used values estimated from several different regions. In addition, the temperature and the hydrogen column density determinations also depend weakly on the data channels used. Ignoring the lower channels (channel 20-40; channels lower than 20 are always neglected because of the low efficiency of the ROSAT/PSPC in that energy range) increases the hydrogen column density and the temperature slightly.

In estimating the cluster mass from the X-ray data, we need to take into account the possibility of temperature gradients existing in the cluster as well as the uncertainty in the value of the overall ICM temperature. Indeed, a recent re-analysis of the ASCA data suggests that there is a significant temperature gradient, with the new estimate of the central temperature in good agreement with the GINGA result (Mushotsky 1995). As the mass estimates depend both on the radial temperature and its gradient (see equation 7-4), it is important to allow for variations away from isothermality. We accomplish this by using the Monte Carlo scheme of Neumann & Böhringer (1995) to determine the total mass profile. Briefly, we generate a temperature profile for the cluster by assigning a temperature, randomly drawn from a pre-defined range (3 to 8 keV in the present case), at equally spaced ($60 \text{ h}^{-1}\text{kpc}$) locations along the radial direction. To prevent unrealistic short-scale oscillations in the temperature profile, we require the temperatures at adjacent locations to be within 0.6 keV of each other. At every step, we calculate the cumulative total mass profile and use only those temperature profiles that give a mass profile that increases monotonically with radius. To obtain an optimal estimate of the mean mass profile as well as the standard deviation, we generate 10^5 temperature profiles and compute the corresponding mass profiles. To ensure that our mass determination includes uncertainties in the gas density profile, we vary the values of (β, r_c) over the range given in Table 1 and repeat the above operations. The projected (2D) profile of the total mass derived from the X-ray data is shown in Figure 18. At the fiducial radius of 3.5 ($\sim 400 \text{ h}^{-1}\text{kpc}$), the projected total mass is $(2.6 \pm 1.6) \times 10^{14} \text{ h}^{-1} M_{\odot}$. As in the case of the gas mass estimates, the projected X-ray mass estimate, unlike the weak lensing estimate, corresponds to the *actual* projected mass within a specified radius.

Combining the above estimates of the gas mass and the total mass determined from the X-ray data yields a gas-to-total mass ratio of $M_{gas}/M_{tot} = (0.06 \pm 0.04) \text{ h}^{-3/2}$. This is consistent with the value derived for the Virgo cluster (Böhringer *et al.* 1994) and a typical value for clusters using the X-ray estimates for the gas and total mass is $M_{gas}/M_{tot} \sim 0.05 \text{ h}^{-3/2}$ (White & Fabian 1995; David, Jones & Forman 1995).

direction	r_c in [kpc/h]	β	n_{e0} in $[\text{cm}^{-3}]$
west	153	0.73	0.0068
	110	0.62	0.0076
south	144	0.78	0.0086
	110	0.67	0.0093
east	206	0.78	0.0064
	158	0.68	0.0069
north	138	0.75	0.0079
	86	0.63	0.0092

Table 1: The results of the isothermal β -fits in the four directions from the hard image derived from the PSPC data (we used the PSPC data for fitting the models, as the statistics in that data set is much better than for the HRI data, due to a lower background.) The two different results for each direction correspond to 3σ -errors. n_{e0} is the central electron number density for 8 keV. The electron density is lowered by about 5% to 10% assuming a gas temperature of 3 keV.

logMplot.ps

Fig. 18.— The 2D mass profile of the cluster. The solid squares are estimates from the weak lensing. The x's are total mass determined from the X-ray gas, with the errorbars being the 2σ dispersion calculated from the 10^5 simulations. The open triangles are the corresponding estimates of the projected gas mass. The solid line is the isothermal model with a velocity dispersion of 1370 km/s and the **X** represents the mass computed by Kneib *et al.* (1995) by modeling the giant arcs.

8. Discussion and Conclusions

In this paper, we have reported on the detection of dark matter in the cluster of galaxies A2218. We found a strong, coherent shear pattern over a scale of $\sim 400''$ from the cluster optical center. Using the weak lensing technique, we have mapped out the dark matter distribution. We have also analyzed the distribution of galaxies, of optical light and of the X-ray emission associated with the cluster.

The combination of the optical, lensing and the X-ray data affords us an unprecedented opportunity to compare the relative distributions of the galaxies, the gas and the total mass in A2218. These distributions are displayed in Figures 7, 8, 15 and 17 respectively. In all of the distributions, the location of the peak (or the dominant peak) corresponds to the location of the central cD galaxy/primary galaxy concentration. There are no strong distinct features associated with the secondary galaxy concentration. In the case of the the light and the mass maps, it can be argued that the lack of such features may be a consequence of the poor resolution resulting from smoothing the maps on scale of $0''.67$. The X-ray map, however, is smoothed on the scale of $0''.23$ and hence, has a much higher resolution.

The contours immediately surrounding the central peak in both the light and the mass maps are elliptical, with the elongation extending in the direction of secondary galaxy clump. The X-ray contours in the immediate vicinity of the peak are also elliptical but with the major axis oriented orthogonal to that of the mass and the light isocontours. The relative orientation of the isocontours in the mass and the X-ray maps are reminiscent of features seen in hydrodynamical simulations of a cluster undergoing a merger with a subcluster (eg. Schindler & Müller 1993). In such events, the X-ray emission tends to trace the lenticular shocks that expand in the direction perpendicular to the trajectory of the infalling subcluster. If this is indeed the case in A2218, then the gas in the central regions would not be expected to be in hydrostatic equilibrium and this may help explain the discrepancy between lensing and the X-ray mass estimates reported by Miralda-Escudé and Babul (1995). However, smoothing the X-ray map on the same scale as the mass and the light maps yields an almost circular surface brightness profile and consequently, it is difficult to ascertain whether both the ellipticity and the orientation of the X-ray contours on scales smaller than $\sim 1'$ are significant.

At distances of $1'-3'$ from the central peak, the extensions in the isodensity contours in the mass map closely follow those in the galaxy surface density plot and to a lesser degree, in the galaxy light distribution. The gas distribution as delineated by the X-ray surface brightness also appears to trace the mass closely. The X-ray map exhibits all of the extensions in the mass map with the exception of the one, the eastern extension.

At projected distances $3'$ ($\sim 340 h^{-1}\text{kpc}$) to $5'$ ($\sim 600 h^{-1}\text{kpc}$) from the cD galaxy, the radial surface density profiles of the cluster light, the intracluster gas and the total mass are all consistent with a $\sim 1/r$ decrease. On these scales, there is no indication of the light or the gas distributions being biased with respect to the total mass.

The projected total mass within a fiducial radius of $3'.5$ ($\sim 400 \text{ h}^{-1}\text{kpc}$) from the cD galaxy, as yielded by the weak lensing analysis, has a lower bound of $M_{tot} = (3.9 \pm 0.7) \times 10^{14} \text{ h}^{-1}M_{\odot}$. This value is in good agreement with the projected total cluster mass inferred from the X-ray data under the assumption that the gas is in thermal pressure-supported hydrostatic equilibrium. Since the projected gas mass interior to $\sim 400 \text{ h}^{-1}\text{kpc}$ is $(1.65 \pm 0.5) \times 10^{13} \text{ h}^{-5/2}M_{\odot}$, the resulting gas-to-total fraction is $M_{gas}/M_{tot} = (0.06 \pm 0.04) \text{ h}^{-3/2}$ if one adopts the cluster mass estimated using the X-ray data and $M_{gas}/M_{tot} = (0.04 \pm 0.02) \text{ h}^{-3/2}$ if one uses the mass estimate derived from the lensing estimate.

Estimating the total stellar mass using a mean mass-to-light ratio of $M/L = 8 \text{ h}$, we find that its contribution to the total baryonic mass is negligible in comparison to the mass in the intracluster gas. The above values of M_{gas}/M_{tot} suggests that the baryonic fraction in A2218, within the central $\sim 400 \text{ h}^{-1}$ is $f_b \approx (0.04 \pm 0.02) \text{ h}^{-3/2}$. Comparing this value to the mean baryonic fraction of the universe expected from nucleosynthesis arguments (e.g. Walker *et al.* 1991) of $f_b \leq 0.015 (\Omega h^2)^{-1}$ suggests that the value of the cosmological density parameter is $\Omega \simeq 0.3$.

Furthermore, adding the light in the field associated with *all* the galaxies gives a lower bound on the mass-to-light ratio in A2218. At the fiducial radius, we find that $(M/L_B) = (440 \pm 80) \text{ h}(M_{\odot}/L_{\odot B})$. If we use only the red light associated with the bright galaxies in the cluster color sequence, we obtain $(M/L_B) = 570 \text{ h}(M_{\odot}/L_{\odot B})$. Here, we have used the lensing mass estimate and have derived the M/L ratio using the total projected mass and luminosity. This ratio remains roughly constant for $r = 180''$ out to the edge of our survey since both the projected light and the surface mass density radial profiles vary with radius in a similar fashion. Converting the above M/L into an estimate of the cosmological density parameter once again yields $\Omega \simeq 0.3$.

The mean surface mass density used to determine the weak lensing mass estimate is, however, calculated by subtracting the mean in the reference annulus extending from $3'.5$ to $6'.2$. Only if the cluster mass distribution drops off sharply beyond $\sim 400 \text{ h}^{-1}\text{kpc}$, then the quoted value of the mass represents the actual value of the projected mass internal to $\sim 400 \text{ h}^{-1}\text{kpc}$. If, however, the cluster mass distribution extends beyond $\sim 400 \text{ h}^{-1}\text{kpc}$ (and hence, into the reference annulus), then the above value is an underestimate. There are indications that the latter is true; for example, the X-ray surface brightness profile extends smoothly out to $\sim 1 \text{ h}^{-1}\text{Mpc}$ and the projected cluster mass continues to rise at least out to $\sim 600 \text{ h}^{-1}\text{kpc}$. If this is indeed so, then the actual value of the projected mass interior to $\sim 400 \text{ h}^{-1}\text{kpc}$ could potentially be much higher. We must caution, however, that this is a highly model-dependent scenario: the isothermal model gives the actual mass being a factor ~ 1.6 higher than our quoted value, while a steeper, Hernquist-type profile gives only a factor of $\simeq 1.2$.

It is tempting to speculate on the consequences of the cluster following an r^{-1} surface mass density profile in the control annulus. In this scenario, we have the following consequences: First,

the lensing mass and the X-ray mass estimates would be discrepant by a factor of ~ 1.6 , with the lensing mass estimate being higher. Interestingly, the level of discrepancy is similar to that in the central regions of the cluster, as discussed by Miralda-Escudé & Babul (1995) and Kneib *et al.* (1995). Second, the gas-to-total mass ratio would drop to $f_b = (0.02 \pm 0.01)h^{-3/2}$, a result that is consistent with the nucleosynthesis value in an $\Omega = 1$ universe. Third, the mass-to-light ratio would also increase to a value as large as $M/L \sim 900$, implying a high value of Ω .

We can, at this point, speculate at length on whether or not the X-ray and lensing mass estimates are indeed discrepant away from the cluster center, and on whether our analysis of A2218 supports the case for high or low Ω . All these issues, however, can be settled observationally by directly probing the weak lensing distortions out to even larger radii and establishing whether or not the mass distribution associated with A2218 drops off sharply beyond a projected distance of $500 h^{-1}\text{Mpc}$. This exciting prospect is now possible with the advent of large-format CCD arrays; for example, the MOCAM device at CFHT has a $14'$ prime focus field. As it comes into its own, the weak lensing technique offers a unique opportunity to resolve many of the outstanding puzzles regarding the dark matter content and distribution in the universe.

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